# A Lightweight, 64-element, Organic Phased Array with Integrated Transmit-Receive SiGe Circuitry in the X Band

Carlos A. Donado Morcillo[1], Chad Patterson[1], Tushar K. Thrivikraman[1], Benjamin Lacroix[1], Bill Wilson[2], Brian Hudson[2], Christopher T. Coen[1], Chung H. J. Poh[1], Ted Heath[2], John D. Cressler[1] and John Papapolymerou[1]

[1]School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA 30332
[2]Georgia Tech Research Institute (GTRI), Smyrna, GA 30080

***Abstract*— For the first time, a transmit-receive (TR), 64-element phased array fully driven by Silicon Germanium (SiGe) integrated circuits and implemented on organic substrates is demonstrated at $9.5\,\mathrm{GHz}$. The array was realized on a duroid and liquid crystal polymer substrate stack-up. The radiating elements are driven by SiGe-based TR modules and power amplifiers. Additionally, radio-frequency micro-electromechanical switches allow the toggled operation between transmit and receive modes. Measurements showed an average TR operation bandwidth of $2.55\,\mathrm{GHz}$, an azimuthal TR beam-steering range of $\pm 26°$, a receive gain of $27.28\,\mathrm{dB}$ and an estimated output power of $41.33\,\mathrm{dBm}$.**

***Index Terms*— Microstrip antenna, organic materials, phased arrays, radar antennas, silicon germanium.**

## I. Introduction

Current and future trends in phased-array technologies for radar and communication applications have been broadly discussed in the available literature [1], [2] (among others). Researchers agree that new developments in phased-array technology should be focused on providing features such as light weight, active-circuit integration, reduced power consumption, conformal mounting capability, scalability, and above all, low production cost. All these features should be taken into account to achieve the best radio-frequency (RF) efficiency by maximizing the output power, the operation bandwidth and the antenna gain while minimizing the noise figure (NF) of the system and optimizing the beam-steering range.

Besides simplifying interconnectivity through the integration of multiple active circuits in a single chip at a reduced power consumption, Silicon Germanium (SiGe) BiCMOS integrated-circuit (IC) solutions have shown remarkable RF performance [3]–[5] at a low production cost. These works demonstrate that it is feasible to integrate phase shifters (PS) with low noise amplifiers (LNA) or with power amplifiers (PA) in a single silicon die, thus, reducing the degradation of the RF performance caused by numerous interconnections.

The aforementioned single-chip SiGe BiCMOS developments have allowed the recent implementation of lightweight, *receive-only* phased arrays in the X and Ku frequency bands [6]–[8]. In these implementations, a PS and an LNA within a single SiGe IC are used to drive individual [6] or several [7], [8] radiating elements in the array. The true benefit of these designs relies on the reduction of the NF of the system as it is significantly improved by placing the active circuitry closer to the radiating elements.

Further reductions in weight and footprint size have been achieved through vertical stack-ups of organic substrates such as liquid crystal polymer (LCP) and duroid [7]–[9]. Additionally, vertical stack-ups of organic materials give physical flexibility which permits the conformal mounting of the arrays without having to trade off future scalability of the system to a higher number of radiating elements. Moreover, vertical stack-ups also reduce the influence of the beam-forming network over the radiation pattern of the array given the ground plane that separates them. The ground plane also allows flexibility of design as it is possible to use different substrate-thickness combinations for the beam-forming network and antennas. In this manner, a thick, low-dielectric-constant substrate can be used for the radiating elements to improve the antenna radiation efficiency; and a thin, high-dielectric-constant substrate can be used for the beam-forming network to reduce the width of the transmission lines, the diameter of via-holes and the size of passive RF components.

The present work takes advantage of SiGe transmit/receive ICs (TRICs) that incorporate an LNA and a three-bit PS that can work in transmit (Tx) or receive (Rx) mode; and integrates them with additional RF MEMS switches (henceforth, MEMS switches) and SiGe PAs to create a full Tx/Rx array. A significant reduction in production costs is intended through the use of high-performance low-cost components such as LCP substrates and silicon-based ICs. To the best of the authors' knowledge, this work demonstrates for the first time the operation of a *transmit/receive* 64-element phased array at $9.5\,\mathrm{GHz}$ using SiGe active circuitry and MEMS switches in a lightweight LCP/duroid stack-up. Design goals include a minimum antenna operation bandwidth of $500\,\mathrm{MHz}$ and a minimum beam-steering range of $\pm 25°$ in the azimuthal direction.

## II. System Overview

Fig. 1 shows the simplified schematic diagram of the 64-element Tx/Rx phased array. The beam-forming network of the array consists of 8 identical rows of active and passive

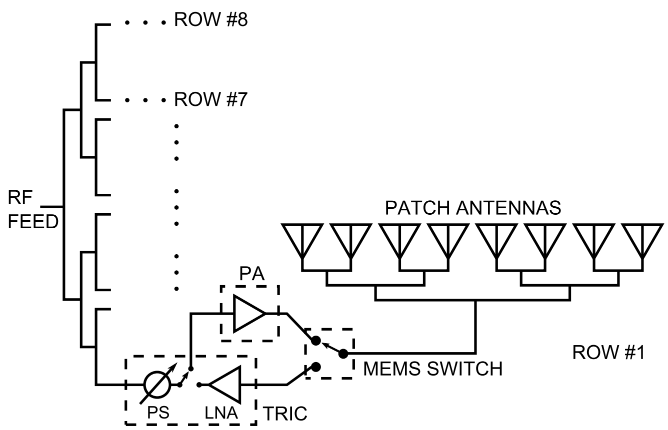



Fig. 1. Simplified schematic of the transmit/receive phased array with SiGe ICs indicated by dashed boxes.

components, each driving a set of 8 microstrip patch antennas, therefore, forming an 8x8 array configuration.

As illustrated in Fig. 1, the Tx and Rx modes are determined in each row by the state of the MEMS switch and of an integrated CMOS switch within the TRIC. In Tx mode (shown), the internal CMOS switch routes the signal from the PS towards the PA, and the MEMS switch, from the PA output towards the patch antennas. In Rx mode, the MEMS switch routes the signal from the patch antennas towards the LNA, and the internal CMOS switch, towards the PS. The TRIC PS is controlled by three "phase" bits that can establish phase shifts of 45°, 90° and 180°, or any combination of them.

The TRIC and PA were designed using a $130\,\mathrm{nm}$ SiGe BiCMOS process (IBM 8HP) with $f_t$ of $200\,\mathrm{GHz}$ and $f_{max}$ of $250\,\mathrm{GHz}$. The TRIC design consisted of a single-stage, hybrid cascode topology with a $0.12 \times 6 \times 4\,\mu\mathrm{m}^2$ high-performance common emitter device and a $0.12 \times 18 \times 8\,\mu\mathrm{m}^2$ common base high-breakdown device. This topology improves output power and efficiency due to the higher breakdown and better voltage knee. In addition, all input and output matching was performed on-chip. The PA on-chip bias circuitry consists of a stable band-gap reference and switched current source that allows consistent operation and quick power-cycle capacity.

Commercial single-pole, double-throw, RF MEMS switches (Radant RMSW220HP™) were used at the interface with the antenna-feed network. The switch provides an isolation of $20\,\mathrm{dB}$ between the Tx output and the Rx input, and an insertion loss of less than $0.45\,\mathrm{dB}$ at $10\,\mathrm{GHz}$. It has a nominal power-handling capability at 10 GHz of $36\,\mathrm{dBm}$ in cold-switching conditions.

Besides the integrated circuits, the beam-forming network includes two sets of $3\,\mathrm{dB}$ splitters. The first set is used to distribute the RF signal to and from the 8 rows containing the TR circuitry, and the second set, to distribute the RF signal to and from the 8 patch antennas of a given row of components. The array elements were designed according to the procedure presented in [8], to provide a constant gain across the broadside azimuthal range between $\pm 25°$.

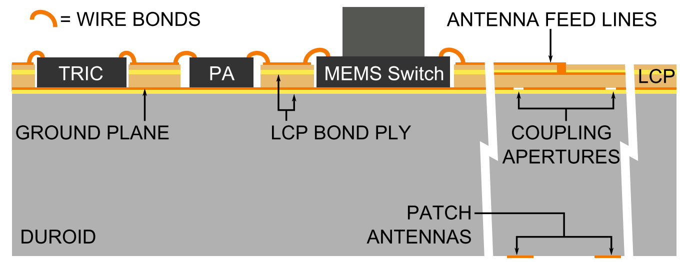



Fig. 2. Cross section of the substrate stack-up showing only 2 patch antennas on the duroid substrate and the beam-forming network components in the LCP substrate.

### A. Substrate Stack-up

The array was implemented in a vertical stack-up (shown in Fig. 2) of the organic substrates liquid crystal polymer ($\varepsilon_{rel} = 2.95$, $\tan\delta = 0.0025$) and RT/duroid 5880 LZ ($\varepsilon_{rel} = 1.96$, $\tan\delta = 0.002$, henceforth duroid substrate). The metallization of all patterned layers is done with copper ($17\,\mu\mathrm{m}$). Transmission lines and ICs are respectively patterned and mounted on an LCP stack-up that has a total thickness of $7\,\mathrm{mil}$ ($177.8\,\mu\mathrm{m}$). The LCP stack is formed by a top LCP core with a thickness of $2\,\mathrm{mil}$ ($\mathrm{LCP}_{2\,\mathrm{mil}}$), and a bottom LCP core of a thickness of $4\,\mathrm{mil}$ ($\mathrm{LCP}_{4\,\mathrm{mil}}$), laminated together through an intermediate LCP bond-ply layer ($1\,\mathrm{mil}$). The RF feed network is patterned on the top side of $\mathrm{LCP}_{2\,\mathrm{mil}}$ and the antenna feed lines are patterned on the upper sides of $\mathrm{LCP}_{2\,\mathrm{mil}}$ and $\mathrm{LCP}_{4\,\mathrm{mil}}$. The ground plane of the transmission lines of the beam-forming network is at the bottom of $\mathrm{LCP}_{4\,\mathrm{mil}}$.

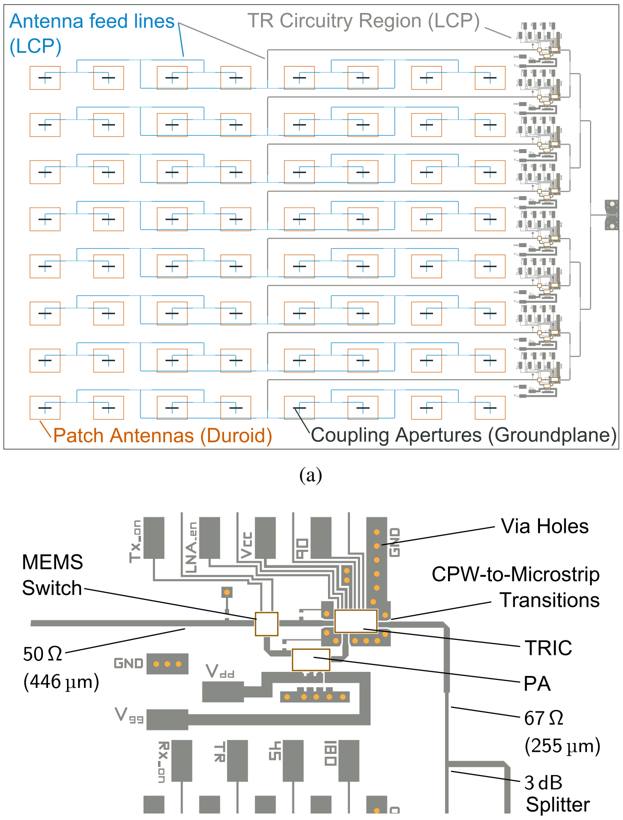
Fig. 2 shows that the LCP stack is separated from the duroid substrate through a copper ground plane that has apertures to couple the patch antennas to the beam-forming network. The duroid substrate is adhered to the ground plane with an LCP bond-ply layer ($1\,\mathrm{mil}$).

A novel feature of this design is the implementation of recessed cavities on LCP where the ICs of the system are mounted (shown in Fig.2). These cavities add robustness to the design by protecting the ICs and by reducing the length of the bond wires that connect the ICs to the RF transmission lines. Shorter bond wires consequently minimize undesired insertion loss and parasitic effects.

### B. Array Digital Control and Power Supply Module

An FPGA (field-programmable gate array) board digitally controls the states of the phase bits along with the TRIC and MEMS switches. Arbitrary phase states and operation modes can be set at any time through a customized computer interface. Three digital lines of $2.5\,\mathrm{V}$ from the FPGA set the phase shift of single or multiple rows at a time, fully automating the orientation of the main beam. An additional TR digital line sets the state of the internal switch of the TRIC for the Tx and Rx modes. Simultaneously, the TR digital line also sets the state of a custom-made driver card that toggles the MEMS switches between the Tx and Rx modes.

In addition, a power-supply module with custom-made cable assemblies was developed to apply feed voltages to the PAs




(a)



(b)

Fig. 3. Phased array layout: (a) Top view of metallization layers in the antenna board (30.4 cm×25.4 cm), and (b) close-up of TR circuitry region.

and to the TRICs and to provide the necessary interconnections. The power-supply board generates 5 V and 3.5 V to respectively feed the common-collector and base bias inputs of the eight PAs. The same 3.5 V output is used to feed the eight TRICs. The 5 V output feeds the MEMS driver card, which provides the switches with 85 V through an external power supply. The total power consumed by all the active components of the phased array is estimated at 601.3 mW.

## III. Design Procedure and Simulations

The system was designed at an impedance of 50 Ω and optimized using Advance Design System 2009 (ADS). Using the method of moments and the geometry of the array, an electromagnetic model was developed taking into account the RF interconnections and the copper traces required by the power supply and digital control lines. Subsequently, a hybrid simulation was performed to incorporate the *measured* scattering parameters (S-parameters) of the packaged TRICs, PAs and MEMS switches with the simulated S-parameters of the RF interconnections. The complete layout of the phased array is shown in Fig. 3(a) and a detailed view of the TR circuitry region is displayed in Fig. 3(b).

The majority of the RF components (passive and active) are interconnected through microstrip lines, with the exception of the TRIC, which requires ground-signal-ground RF connections. For this reason, microstrip-to-coplanar-waveguide transitions were designed from the interconnection of the TRIC to the RF feed lines. Via holes are deployed to connect the ground pads of the coplanar waveguide (CPW) sections of the transitions to the ground plane of the array.

## IV. Fabrication and Measurements

The antenna board was metallized and laminated at an external facility, where also the recessed cavities in the LCP substrate were laser-milled. The SiGe IC's were also fabricated at an external facility. The SiGe ICs, MEMS switches and additional passive components such as biasing resistors, and bypass capacitors were mounted on the board using silver epoxy. 3 mil ribbon bonding wires were used to connect all the integrated circuits to the RF transmission lines, as well as to the digital control lines and power-supply lines. Finally, a detachable SMA female connector was mounted at the array input for radiation pattern and S-parameter measurements.

Fig. 4 shows the measured return loss in Tx and Rx modes. Both plots demonstrate an antenna bandwidth below 10 dB across the 9.25 GHz-9.75 GHz band. In fact, the total Tx bandwidth covers a band of about 2.675 GHz and the Rx bandwidth, of 2.43 GHz to give an average TR operation bandwidth of 2.55 GHz, which exceeds the design goal of 500 MHz.

The radiation pattern measurements were taken in a fully automated anechoic chamber (Fig. 5). The power supply/digital control module was covered with RF absorbers to increase the accuracy of the measurements. A laptop computer was used to set the different phase states of the rows in the array. Fig. 6(a) illustrates the results of the co-polarization measurements in Rx mode with a maximum peak gain of 27.28 dB at boresight. From the maximum gain lobe we can obtain a broad-side 3 dB beam-width of approximately 10°. As expected, the peak gain decreases to 26.14 dB at an angle of 24°, on the other hand, the signal falls to 26.35 dB at −28°, giving a receive beam-steering range of ±26°. Cross-polarization measurements were also performed and a maximum level 30 dB below the maximum array gain was observed, indicating that the cross-polarization radiation is negligible. In Tx mode, measurements

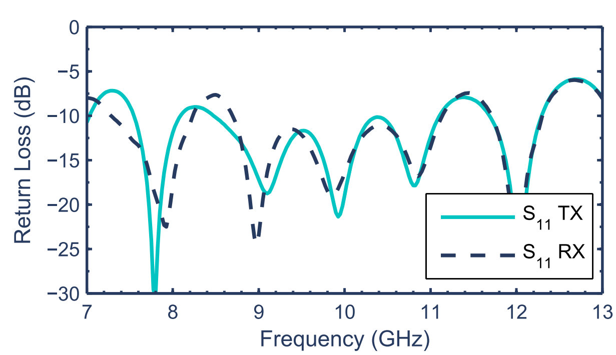



Fig. 4. Measured return loss of the phased array.

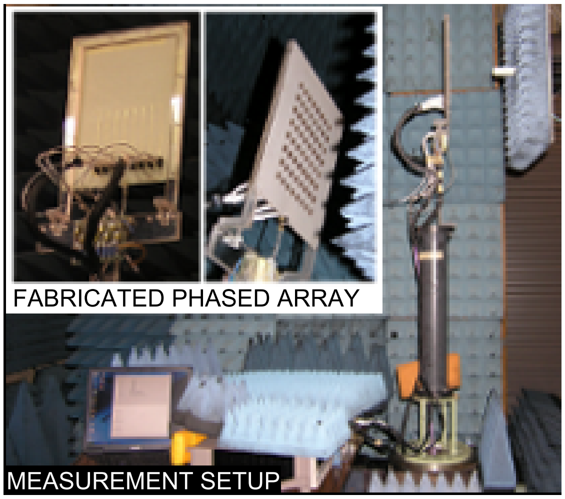
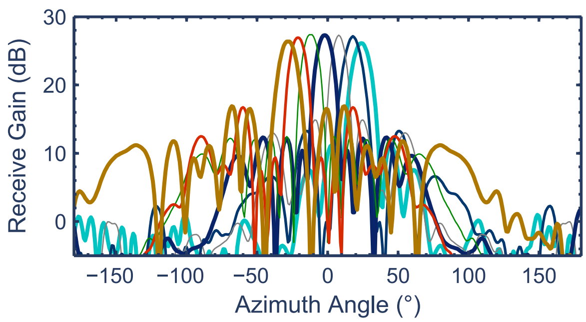
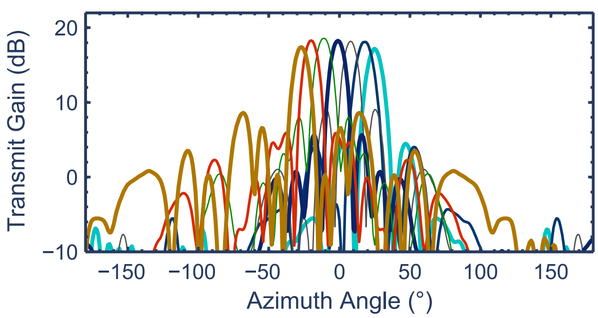



Fig. 5. Fabricated phased array and measurement setup.




(a)




(b)

Fig. 6. Co-polarization radiation pattern measurements at different azimuthal steering angles (a) Rx mode, (b) Tx mode.

showed (Fig. 6(b)) a steering range of $\pm 26.5°$ and a peak gain of $18.57\,\mathrm{dB}$ at $-11°$, followed by the slightly lower boresight gain ($18.24\,\mathrm{dB}$). The $0.33\,\mathrm{dB}$ difference between these two peak gains is attributed to slightly dissimilar operating points among the 8 PAs.

The effective isotropically radiated output power (EIRP) can be calculated using the approach presented in [5]. However, this approach requires the knowledge of the gain of individual radiating elements in the array and the losses of the network between the output of the PA and the antennas. Although the individual antenna gain and loss of the output network could be obtained through simulation, we propose an accurate calculation to estimate the EIRP by referring the PA output power at saturation to the RF feed of the phased array, and then applying the measured transmit gain at boresight.

A hybrid simulation taking into account the S-parameters of the input network indicates that the insertion loss from the array feed to the output of one PA is $9.26\,\mathrm{dB}$. Thus, added to the *measured* saturated power of the PA ($13.5\,\mathrm{dBm}$), the required total input power becomes $22.76\,\mathrm{dBm}$. This figure is then added to the maximum transmit gain at boresight ($18.57\,\mathrm{dB}$) to obtain an estimated EIRP of $41.33\,\mathrm{dBm}$.

## V. Conclusion

The TR operation of an organic 64-element array was demonstrated for the first time. A maximum receive gain of $27.28\,\mathrm{dB}$ was measured in the broadside and a total radiated power of $41.33\,\mathrm{dBm}$ was estimated. Future efforts will focus in increasing the output power of the SiGe PA, as well as moving the SiGe ICs closer to the antenna element by innovative packaging techniques.

## Acknowledgement

The authors recognize the work of Demetrius James from GTRI in the implementation of the power supply module. This work was supported by the National Aeronautics and Space Administration (NASA) under grant #NNX08AN22G.

## References

[1] P. Schuh, R. Rieger, A. Fleckenstein, M. Oppermann, B. Adelseck, H. Mussig, and H. Brugger, "T/R-module technologies today and possible evolutions," in *Proc. RADAR Radar Conf. - Surveillance for a Safer World Int*, 2009, pp. 1–5.

[2] Y. Mancuso, P. Gremillet, and P. Lacomme, "T/R-modules technological and technical trends for phased array antennas," in *Proc. European Microwave Conf*, vol. 2, 2005.

[3] T. K. Thrivikraman, W.-M. L. Kuo, and J. D. Cressler, "A two-channel, ultra-low-power, SiGe BiCMOS receiver front-end for X-band phased array radars," in *Proc. IEEE Bipolar/BiCMOS Circuits and Technology Meeting BCTM 2009*, 2009, pp. 43–46.

[4] K.-J. Koh and G. M. Rebeiz, "An X- and Ku-Band 8-element phased-array receiver in 0.18-mum SiGe BiCMOS technology," *IEEE J. Solid-State Circuits*, vol. 43, no. 6, pp. 1360–1371, 2008.

[5] A. Valdes-Garcia, S. T. Nicolson, J.-W. Lai, A. Natarajan, P.-Y. Chen, S. K. Reynolds, J.-H. C. Zhan, D. G. Kam, D. Liu, and B. Floyd, "A fully integrated 16-element phased-array transmitter in SiGe BiCMOS for 60-GHz communications," *IEEE J. Solid-State Circuits*, no. 99, pp. 1–17, 2010, early Access.

[6] Y. A. Atesal, B. Cetinoneri, K.-J. Koh, and G. M. Rebeiz, "X/Ku-band 8-element phased arrays based on single silicon chips," in *Proc. IEEE MTT-S Int. Microwave Symp. Digest (MTT)*, 2010, pp. 1258–1261.

[7] C. Patterson, T. Thrivikraman, A. Yepes, S. Begley, S. Bhattacharya, J. Cressler, and J. Papapolymerou, "A lightweight organic X-Band active receiving phased array with integrated SiGe Amplifiers and phase shifters," *IEEE Trans. Antennas Propag.*, no. 99, p. 1, 2010, early Access.

[8] T. Thrivikraman, C. E. Patterson, A. M. Yepes, T. Heath, B. Wilson, J. Papapolymerou, and J. D. Cressler, "Integrated, digitally-controlled, 64 element SiGe on multilayer organic X-band phased-array receiver antenna for snow measurements," *IEEE Transactions on Microwave Theory and Techniques*, submitted for review in October 2010.

[9] J.-C. S. Chieh, A.-V. Pham, T. W. Dalrymple, D. G. Kuhl, B. B. Garber, and K. Aihara, "A light weight 8-element broadband phased array receiver on liquid crystal polymer," in *Proc. IEEE MTT-S Int. Microwave Symp. Digest (MTT)*, 2010, pp. 1024–1027.